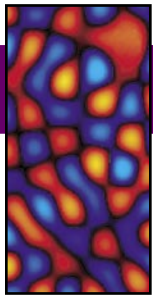

Fault Detection and Localization Using Laser-Measured Surface Vibration

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INTRODUCTION

Structural health monitoring techniques have become increasingly important to the Navy of the 21st century whose strategy is to emphasize advanced designs and new material technologies in its modern high performance structures while utilizing existing aging structures beyond their planned lifetimes. At the same time, the Navy would like to reduce manning levels on Naval platforms, reduce time in repair and total ownership costs, and increase survivability. Among other things, these trends have driven the need for the development of reliable, automated, structural health assessment methodologies. In response to this need, we have been addressing the feasibility of structural acoustic techniques for monitoring the mechanical condition of structures.

The focus of our structural acoustic development efforts thus far can be summarized by the following question: Given sufficient but readily accessible displacement information over the surface of a vibrating structure, can we develop and implement corresponding *local* inversion algorithms for mapping material parameter variations, detecting and localizing flaws (such as cracks, voids, and delaminations), and uncovering the depth profiles of such?

In this article, we present the details of the structural acoustic approach to fault monitoring, describe various "inversion" algorithms for extracting the fault information, show the results of numerical feasibility studies, discuss the associated measurement technologies, and then present applied studies we have carried out using this methodology. These include both laboratory-based studies on simple structures and spin-off work we have done on art-laden walls at the U.S. Capitol building.

THE STRUCTURAL ACOUSTIC APPROACH

Mechanical fault monitoring using the dynamic response of a structure excited by externally applied forces is not new. For the most part, traditional methods involve some application of modal analysis techniques that typically extract changes in resonance frequencies and/or associated mode shapes. One drawback of such modal approaches results from the fact that local changes in a structure caused by a fault often produce only very small changes in these global modal parameters whereas unavoidable environmental changes can have a large impact on these measured characteristics. In addition, even when modal analysis is used successfully to indicate a structural problem, localization of the detected flaw is in general difficult.

Our focus has been to develop techniques that not only use the traditional mechanical dynamic response but also are able to detect and characterize *local* changes in the structural dynamics caused by the presence of a fault. Figure 1 illustrates this methodology, which uses measurements of surface displacement associated with vibration of the structure caused by externally applied forces. These forces can be created simply by a local actuator in direct contact with the structure or in some cases by an incident airborne acoustic wave. The measured normal surface displacements $u_z(x, y)$ are then inverted *locally* by using various mathematically optimized algorithms in order to obtain a desired material parameter—for example, the elastic modulus—whose spatial variation then serves to detect and localize the fault. We choose to rely on *surface* displacements because these are readily accessible for all materials and for most structures using existing scanned sensor technologies, such as laser Doppler vibrometry. There are techniques capable of interior displacement measurements, including magnetic resonance elastography (MRE) and various optical scattering methods, but these can be applied only to a restricted set of materials—those with high proton spin density for MRE and those that are optically transparent for the latter.

INVERSION ALGORITHM EXAMPLES

To a large extent, the power of the fault detection techniques pursued here depends on the successful development of a compatible set of inversion algorithms that can operate efficiently and in the presence

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Fault Detection and Localization Using Laser-Measured Surface Vibration**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue SW,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

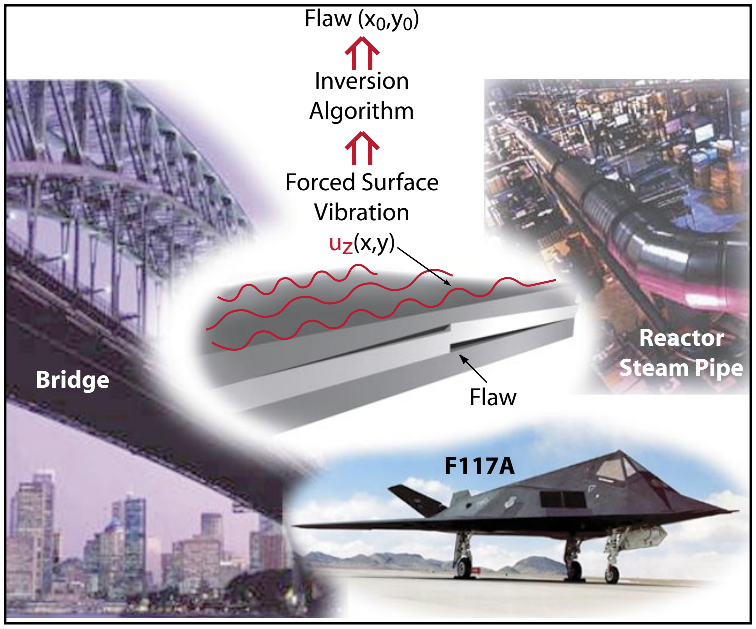


FIGURE 1
Depiction of the structural acoustic fault monitoring methodology applied to a variety of structures. Surface displacements are monitored over the area of interest due to structural vibrations induced either by an applied shaker or an acoustic source. The displacements measured over the surface are algorithmically inverted to produce a map of a desired material parameter that serves to detect and locate the flaw.

of noise on the scanned surface displacements of the vibrating structure to produce a meaningful map of some fault-sensitive mechanical parameter. Below we discuss four such algorithms with which we have had various degrees of success.

Direct Inversion

In the direct inversion approach,[1] we seek to invert the equations of motion for the structure. For the vibration of general elastic media at frequency ω, the fundamental equation is given as

$$\sigma_{ij,j}\,[\vec{u}] + \rho\,\omega^2 u_i = f_i, \qquad (1)$$

where σ_{ij} is the stress, the subscript j denotes the partial derivative with respect to co-ordinates x_j, $\vec{u}$ is the displacement, ρ the density, and $\vec{f}$ the applied force used to vibrate the structure. Without detailing the mathematics here, in locations away from the applied force, a variational form of the above equation is constructed through multiplication by a smoothly varying "virtual" function having specifically designed boundary conditions and insertion of the relevant relationship between stress and strain. The resulting equation is then inverted to obtain an effective elastic modulus in terms of the measurable displacements $\vec{u}$. For the case of a plate structure of thickness h, Young's modulus E, and Poisson ratio υ, the inversion results in the relatively simple relationship

$$M(E, \upsilon, \rho, h) = \omega^2 G(u_z), \qquad (2)$$

where M is the *local* plate stiffness/(ρh) and G is an integral function over the surface whose integrand depends upon the measured $u_z(x,y)$ and which by design contains no spatial derivatives of u beyond the first. We will show later that this latter property, which results from introduction of the virtual functions, is important because of its ability to greatly reduce the effects of spatially dependent noise on the inversion result. The simple application of Eq. (2) on the measured displacements can thus provide *local* mechanical information involving E, υ, ρ, and h.

Generalized Force Mapping

In contrast to direct inversion, the generalized force mapping technique[1] uses the *known* values of the elastic moduli, density, and thickness together with the measured displacement $u_z(x,y)$ across the surface to compute the left-hand side of Eq. (1). Away from the applied force, a non-zero result here as a function of position identifies a *generalized* force that now exists in the plate as a consequence of the presence of the flaw. The appearance of these forces together with their position then serve to detect and locate the fault. In principal, the details of the derived force could be used to further characterize the fault, although we have not yet exploited this possibility.

ω-*k* Mapping

In ω - k mapping,[2] a two dimensional temporal and spatial FFT is performed on the measured

displacement data thus providing a frequency (ω) - wavenumber (k) representation of the elastic vibration. These transforms are spatially windowed to provide *local* information. For elastic wave propagation, this format displays characteristic "dispersion" curves indicating the elastic wave types present (e.g., compressive, shear, and flexural) and the frequency dependent velocities. Local differences in these curves from those observed or expected in unflawed structures indicate variations in wave types or in their speeds that are directly related to material parameter variations associated with the development of flaws. This Fourier acoustic technique has been particularly successful when applied to delamination effects in layered structures. In such cases, slow flexural waves excited in the detached layer present their unmistakable $\sqrt{\omega}$ dispersion curves in distinct contrast to the nearly vertical lines of the faster waves traveling in the uncompromised, adhered structure.

Dot Product/Cross Correlation

In the dot product/cross correlation approach, the frequency spectra of the displacements at each data location are viewed as a multicomponent vector. Using this perspective, a vector dot product is performed between spectral data obtained at two separated locations; and with one of these points fixed, the resultant projection is mapped onto the surface. This approach highlights local differences in spectra providing a good indication of material parameter fluctuation across the structure.

NUMERICAL DEMONSTRATION

An effective way to illustrate the workings of an inverse algorithm and to evaluate its expected performance is through numerical simulation. We focus discussion of our numerical studies on the case of a solid homogeneous metal plate with and without an internal inclusion near its upper left-hand corner. In the context of fault monitoring applications, plate results are more general than one might first think in that many structures can be addressed at some level as a collection of platelike elements. A finite-element structural dynamics code is used to compute the dynamic displacements $u_z(x, y, \omega)$ on a rectangular grid with a spacing much less than the fault size. In an actual system, it is the parameter u that would be monitored over the structure's surface and then used as an input to an inversion algorithm.

We consider the more typical case in which the displacement data itself does not directly reveal the presence of the flaw. For such a case, Fig. 2 shows the results of applying three inversion algorithms to displacement "data" obtained at 20 kHz in steel plates 60 × 30 × 2.54 cm, one having a 2 × 1 × 1.5-cm inclusion, whose Young's modulus is 0.05 that of the plate.

Figure 2(a) shows the displacement "data" for both the homogeneous plate and the plate with the inclusion. Clearly, there does not appear to be any definitive indication of the location of the flaw in the displacement data itself. Figure 2(b) shows the result of applying the variational inversion algorithm specified by Eq. (2). In both plates, the somewhat regular modal pattern seen throughout the elastic modulus map is an artifact of the inversion algorithm operating on the zero displacement levels (i.e., $u_z = 0$) that exist at the nodal lines of a mode. This particular inversion algorithm is not properly conditioned to handle these zero levels. We have shown that this modal structure in the elastic moduli maps can be eliminated by using broadband data so that the nodal lines for any particular mode do not lead to zero displacement levels anywhere across the plate. One method we have developed to accomplish this is called the |VV*| algorithm, which sums, at each spatial point and over each frequency component in the band, the absolute square of the magnitude of the measured normal velocity. (Note that the velocity is the time derivative of the displacement u.) We show an example of how the algorithm is used |VV*| later when we discuss experimental results.

Ignoring these nodal line artifacts, one can clearly see the rectangular flaw in the upper left-hand corner of the modulus map. Further, the color map gives the correct value for the ratio of the bending modulus $Eh^2/(12(1-\upsilon^2))$ of the flawed region vs the homogeneous region (0.3), a parameter that can be used to further characterize the fault. To demonstrate the importance of developing the "variational" formulation of the inversion algorithm, we apply a simpler flexural inversion algorithm to the displacement data and show the results in Fig. 2(c). As can be seen, in addition to the pattern associated with the nodal lines, there exists a finer scaled pattern as well. This is an artifact of this algorithm associated with the presence of high-order (up to the fourth) spatial derivatives operating on the discretized (and therefore "noisy") displacement data generated by the finite-element calculations. As discussed previously, this effect is all but eliminated when applying the variational inversion algorithm (Eq. (2)) because in the expression for G, the higher order derivatives operate on the smooth, noiseless virtual functions unlike the simpler inversion algorithm where they instead operate directly on the "measured" data $u_z(x, y,)$.

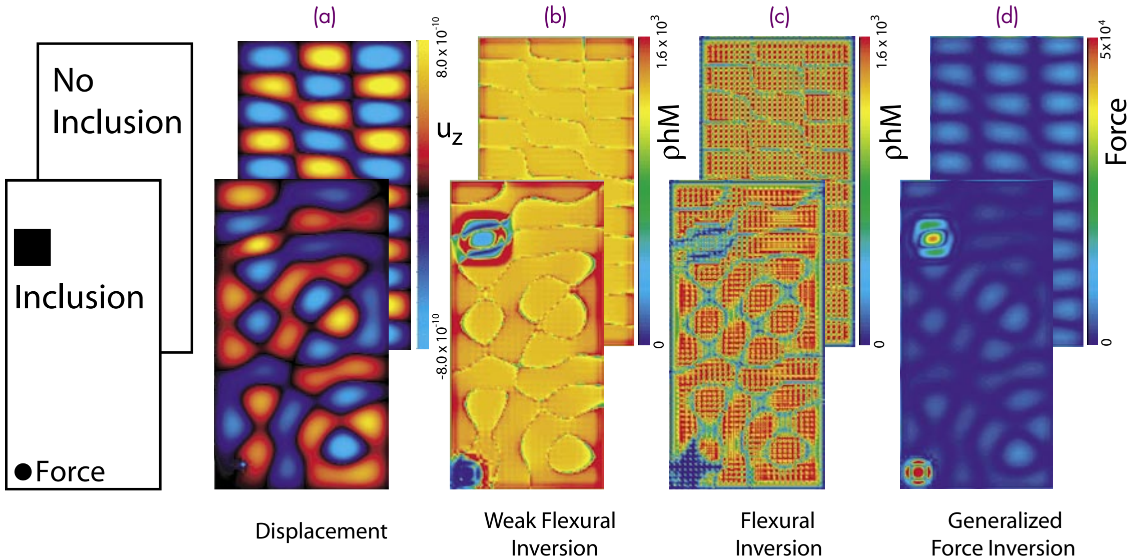


FIGURE 2
Results of a finite-element-based numerical study to detect and locate an internal inclusion in a steel plate. The upper and lower rows are for the cases of the homogeneous plate and the flawed plate respectively. Column (a) displays the "measured" surface displacements. The next three columns show the results for applying three different inversion algorithms to the surface displacements, (b) variational flexural inversion designated by Eq. (2), (c) flexural inversion, and (d) generalized force inversion.

Next we consider application of the generalized force mapping algorithm wherein we assume known values for the elastic plate parameters, computing the left-hand side of a variational form of Eq. (1) using these and the measured displacement data. Non-zero values indicate internal forces in the structure associated with the inclusion. Figure 2(d) shows the results for the homogeneous plate (upper figure) and for the plate with the inclusion (lower figure). As can be seen, the generalized force map does clearly detect and locate the inclusion (and of course the applied force as well). Compared to the elastic moduli inversion algorithms, this algorithm is not so affected by the presence of nodal lines.

APPLIED STUDIES

Laboratory Studies

Experimental studies conducted in the laboratory indeed confirm the efficacy of implementing structural acoustic fault detection methodologies. In addition, the experiments have been used to develop practical implementations of these concepts wherein we have addressed shaker and acoustic speaker methods for mechanically exciting the structure; acquisition of broadband, surface-scanned displacement data; and the performance of the inversion algorithms in real structures.

We have implemented two techniques for acquiring the surface displacement data. The first is a commonly used technique employing a scanning laser Doppler vibrometer (SLDV). In addition to special laboratory designed devices, there are commercially available SLDV systems that are ideal for this function, some of which have software allowing versatility in choosing spatial sampling intervals as well as specific surface sampling paths. Typically, the analog output of the SLDV is band-passed filtered and stored digitally for the postprocessing by which we implement the inversion algorithms. A second less well-known surface displacement measurement technique uses a miniature scanning acoustic microphone to sample the evanescent sound *pressure* field emanating from the vibrating structure. Using the principles of nearfield acoustic holography (NAH),[2] we have taken the measured pressure fields and back-projected them onto the structure's surface, converting them to spatial displacement information, i.e., $u_z(x,y)$.

Using these actuation and displacement measurement techniques, we have studied and successfully demonstrated our structural acoustic fault detection methods on a number of relatively simple laboratory structures. These include metal plates with flaws, lap joints with varying degrees of attachment, and thin, stiffened panels with segments of frame detachment.

An illustrative and important example of these studies is that carried out on frame-stiffened plates and

composite panels. Our interest here is related to composite airframe structures and the need to detect and locate areas where problems are developing along the frame/skin bond. Figure 3(a) shows the ribbed side of a stiffened plate, and Fig. 3(b) shows the underside of the plate showing the location of the detached frame segment (red rectangle). Figure 3(c) shows an SLDV-measured displacement scan made on the topside of the plate, and Fig. 3(d) shows the result of operating the variational inversion algorithm on these data. In this latter map, dark blue vertical lines successfully track the locations of the hidden interior frames, and the associated gap in the middle of the center frame line successfully indicates where the frame has become detached. We have produced virtually identical results for thin, frame-stiffened composite panels of the type used in air-frame structures, examples being the wing skins, control surfaces, and stabilizers of fighter aircraft.

Microstructure Monitoring

Even though our discussion has centered on fault morphologies whose sizes fall in the centimeter to millimeter range, the structural acoustic method does not appear to be limited to any particular length scale. Indeed, the inversion algorithms themselves are independent of scale. What is required is that the structure be mechanically excited at frequencies whose structural wavelengths are short enough, no more than an order of magnitude larger than the fault dimension, and that the dynamic surface displacements be mapped with a spatial resolution an order of magnitude smaller than the fault size. Thus, for example, 10-μm flaws could be detected and localized near the surface of a typical solid using an excitation of several megahertz and a surface vibration measurement capable of a several micron resolution. That the structural acoustics methodology can be focused, as it were, down to relatively small dimensions has important implications for the detection and characterization of microflaws in many solid materials, including metals, composites, ceramics, and semiconductors.

By way of example, we have in fact successfully employed microscope SLDVs developed at NRL with super resolution to map the vibration over the surface of micron-thick silicon crystal micro-oscillators in the form of rectangular paddles about 100 μm on a side. In so doing, we have been able to detect and locate various faults in our fabricated structures. For example, consider the measured displacement map shown in Fig. 4 for a 373 kHz paddle vibration mode

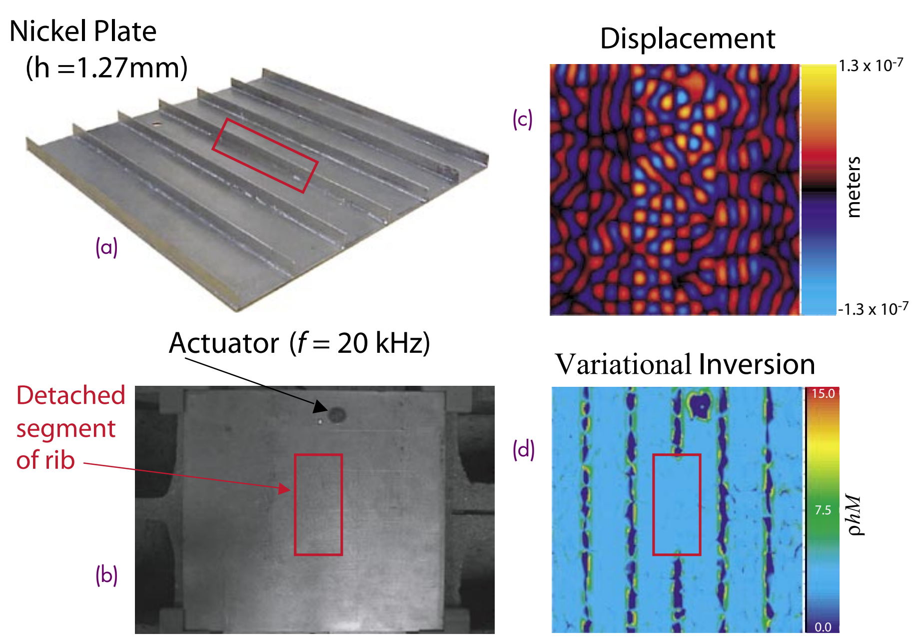


FIGURE 3
Experimental demonstration to detect and locate frame detachment in a rib-strengthened thin nickel plate. (a) Shows the ribbed side of the plate, and (b) shows the external measurement side with the red rectangle marking the hidden location of frame detachment. (c) Shows the SLDV-measured surface displacements caused by a point actuator in contact with the plate excited at 20 kHz, and (d) shows the result of applying the variational flexural inversion algorithm, where the obscured frames manifest themselves by the deep blue lines and the detached region by the absence of such.

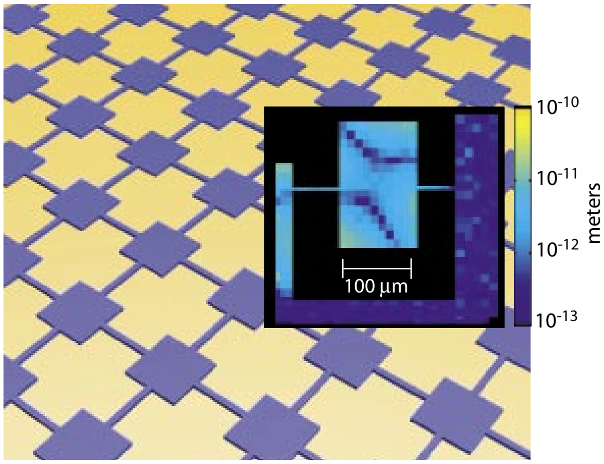


FIGURE 4
The insert displays microscope SLDV measurements of the dynamic displacements of a 100 µm silicon paddle oscillator and that of its supporting structure excited at 373.3 kHz. The color scale goes from 10^{-13} m (deep purple) to 10^{-10} m (yellow). Note the comparably large motions of the left-hand support structure, an unintended consequence of undercutting in the chemical etching fabrication process. The background illustrates a multielement array of paddle micro-oscillators with the inter-oscillator coupling produced by the narrow silicon beams.

where one can readily see comparable motions of the left support, a structure intended to be rigidly attached to the substrate but which had become released by unintentional undercutting in the chemical etching fabrication process. Further, NRL has extended the spatial resolution of its laser vibrometers down to tens of nanometers using the very near field of a tapered optical fiber tip.[3] The ability to generate such high resolution dynamic displacement maps together with the associated inversion algorithms will become an important tool in our work to understand the vibrational behavior of large arrays of interconnected micro-oscillators (background structure in Fig. 4). In these so-called "phononic crystals," our structural acoustic techniques will be able to reveal the *mechanical* condition and behavior of these structures, particularly that of the critically important interoscillator coupling members.

Assessing Wall Paintings and Underlying Structure at the U.S. Capitol Building

The structural acoustic fault detection methodologies developed here have applications beyond military structures. For example, the authors were invited to demonstrate and evaluate their new fault detection and localization techniques for assessing the integrity of art-bearing walls and ceilings in various rooms in the U.S. Capitol. The United States Capitol building (both House and Senate) has large expanses of important fine art and decorative paintings[4] executed directly on the original lime plaster. In support of a comprehensive infrastructure modernization program in the building, the integrity of the supporting structures is being evaluated so that degradations underlying the artwork can first be located and repaired.

The frescoes were painted in the nineteenth century by the Italian artist Constantino Brumidi[4] on a roughly 2-cm-thick structure consisting of three layers of plaster of varying composition supported by a thick masonry foundation. A successful nondestructive evaluation technique must be able to detect defects throughout the structure, including loss of cohesion within a plaster layer and delaminations between the layers or at the attachment of the mortar to the supporting wall structure.

Figure 5(a) shows the typical setup we used to carry out preliminary diagnostic studies, in this particular case for the Brumidi Corridor of the Senate Wing. Panels on the wall or ceiling were excited over a band of frequencies by the use of either a broadband shaker applied directly at a point on the structure or an acoustic speaker that exposed the walls and ceiling to acoustic energy. A scanning laser Doppler vibrometer was used to map the small-scale vibratory motion of the wall or ceiling over the area of interest using a serpentine grid pattern with a spacing of several centimeters. In addition to the Brumidi Corridor, measurements were also carried out in the Senate Reception Room, The President's Room (Fig. 5(b)), The House Appropriations Committee Room, The Parliamentarian's Office, and the Office of The Speaker of The House.

In general, our techniques were very successful at detecting and locating faults when they existed in the structure underlying the art. We were able to identify a variety of problems including areas of unconsolidated plaster, various size regions having delaminations between plaster layers, and places where there is complete detachment of the plaster from its typically brick foundation. Overall, our SLDV-based structural acoustic approach compared favorably to other techniques used at the Capitol including those employing radar and thermal imaging.

Figure 6 shows a result we obtained on a panel in the Brumidi Corridor. Figure 6(a) shows a *quantitative* color map representing our measured displacement data after processing with the |VV*| algorithm, which sums the absolute magnitude of the measured normal velocity at each spatial point and over each frequency bin. This clearly indicates six or so localized faults. They are attributed to simple, small areas of

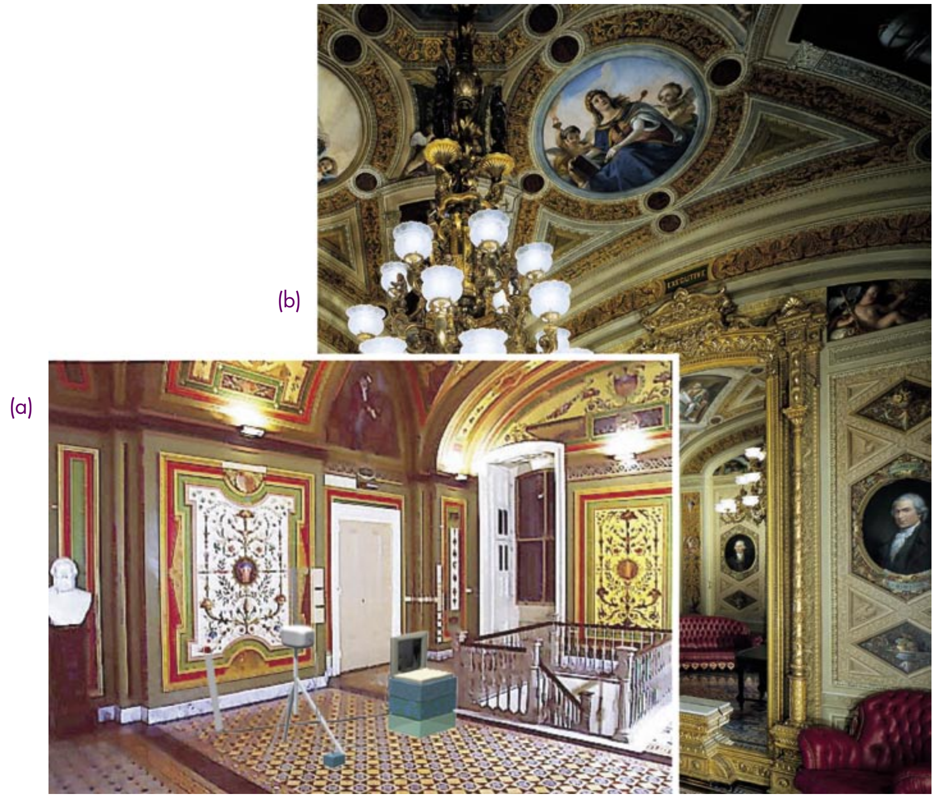
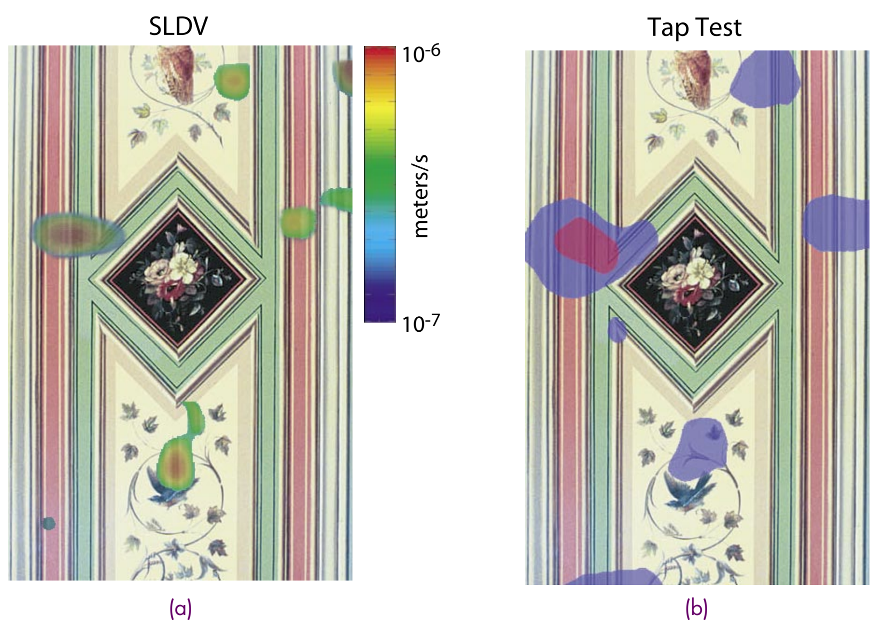


FIGURE 5
(a) Experimental arrangement for plaster wall assessments at the U.S. Capitol building showing the SLDV monitoring system, a shaker used to excite the art-laden walls, and a laptop computer data acquisition system in the Brumidi Corridor. (b) The President's Room where extensive measurements were made on the walls and ceiling.

FIGURE 6
A comparison of the faults found by (a) our structural acoustic technique and by (b) a tap test in a fresco panel in the Brumidi Corridor of The U.S. Senate. Our technique is the result of the VV* algorithm, with the color scale showing velocity in m/s for a one newton force applied to the wall. The tap test is a labor-intensive, time-consuming process wherein a skilled practitioner taps sequentially with a small hammerlike tool on a large number of points on the surface while listening with his unaided ear to the audible response of the wall, from which he locates underlying faults.



delamination between the innermost plaster layer and its attachment to the brick supporting structure. In this particular case, the results can be compared to the available findings from what is called a "tap" test. In this age-old technique, a skilled conservator literally taps sequentially with a small hammerlike tool on a large number of points on the surface while carefully listening with his unaided ear to the audible response of the wall from which a *qualitative* fault map is generated. Although an experienced, skilled practitioner can often identify the existence (and sometimes type) of inhomogeneity, this is an impractical method for gathering—much less recording—such information, especially over large expanses. Nonetheless, Fig. 6 shows satisfying agreement between our laser-automated, quantitative, rapid method and the time-consuming, human-discerned result.

ON-PLATFORM SENSOR TECHNOLOGIES

Our discussion so far has focused on displacement monitoring techniques (laser Doppler vibrometry and NAH-processed microphone scans) in which the sensing is remote from the structure. Both these techniques can provide ultrahigh spatial sampling rates, an ideal feature for implementing our high spatial resolution inversion algorithms. There are cases, however, for which these remote sensing techniques are either geometrically impractical or undesirable from a data collection viewpoint. For such cases, we have been considering on-platform sensor technologies, which have potential for our fault monitoring methodology. Three attractive examples include multiplexed arrays of fiber Bragg grating (FBG) sensors, arrays of fiber-optic intensity (FOI) accelerometers, and wireless arrays (WA)[5] of electrical accelerometers.

The first two optically based techniques—FBG and FOI—have the advantage of immunity to electromagnetic interference, an important attribute in high-field environments. It is reasonable to speculate today that both techniques could be pushed to sensor counts in the hundreds, numbers that would be required for covering areas 10 to 30 times the fault size. Based on today's costs, large arrays of either type would not be inexpensive, with the less-costly being the FOI array. Wireless sensor arrays inspired by modern cell-phone systems are beginning to appear in a number of engineering applications, and the absence of signal wires or fibers would offer a great practical advantage in implementing our fault monitoring concepts. In such an array, wireless sensor/radio nodes would be distributed over the structure's surface. We estimate that as many as one thousand sensor/radio pairs could be deployed over a specific cell with many such cell sites communicating their multisensor information to a common base station. Such a sensor array with 10,000 nodes perhaps covering an area a thousand times the fault size would require less than a watt of power!

CONCLUDING REMARKS

The structural acoustic methodology discussed here offers a reliable, practical approach to mechanical health monitoring in a variety of structures important to the Navy, the DoD, and the Nation in general. It combines the suffusive nature of broadband structural vibration with the power of carefully designed inversion algorithms in order to detect and *locate* various faults within platelike structures. The methodology has general application, from large-scale structures, such as ships and aircraft, down to micro- and nanostructures. This approach is relatively new, and as the sophistication of the inversion algorithms grows, the fault detection performance and its identification ability will continue to advance. So far, we have addressed a number of applications and for the most part have implemented the techniques using a manually placed SLDV. As the future unfolds, we expect to also integrate structure-mounted sensors using emerging high-count sensor array technologies.

ACKNOWLEDGMENTS

The authors acknowledge the many technical contributions to these efforts of a number of colleagues, especially Drs. Brian Houston, Phil Abraham, Jim Tressler, Saikat Dey, Barbara Marchetti, Enrico Esposito, Andrew Kurdila, and Mr. George Adams. We also thank Leslie Chaplin for her efforts in preparing the artwork.

[Sponsored by ONR and The Architect of The Capitol]

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